Performance evaluation of LTE in unlicensed bands for indoor deployment of ultra-broadband mobile networks

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***Abstract*—The continuous growth of worldwide mobile subscriptions and the progress of mobile devices and telecommunications in the last few years has led to a tremendous increase of demand for high data rates. The scarcity of licensed spectrum and the high costs of this resource have encouraged mobile operators to move towards the unlicensed spectrum. LTE Licensed-Assisted Access is the proposed technology, that allows to work on the 5 GHz unlicensed band. To operate on these frequencies already occupied by Wi-Fi and radar systems, LTE must fairly coexist with the above. The aim of this paper is to analyze the downlink performance improvements, offered by the aggregation of unlicensed bands, in terms of user throughput.**

***Index Terms*—LTE LAA, coexistence, LBT, Wi-Fi, 5G, ns-3**

I. Introduction

In the last few years with the massive spreading of smartphones and the evolution of communication technologies, there has been a substantial change of services required by the growing number of mobile subscribers. In fact, between the first quarter of 2015 and the first quarter of 2016 the data traffic grew of the 60% worldwide [1]. As a sign of this transformation of use cases, it can be observed that the main factor of the traffic growth is represented by video contents.

To grant better user experience, mobile operators have to deal with an increasing demand for high data rates. LTE-Advanced has allowed significant improvements in this regard both enhancing spectral efficiency and increasing bandwidth, with the introduction of higher order modulations, MIMO technology and Carrier Aggregation. In particular, the use of greater amounts of spectrum is a key issue to achieve higher network capacity. From this viewpoint, finding new available spectrum is not easy for mobile operators because of the limited nature of the resource and the great costs of licensed frequency bands. Hence, this obstacle has led to look for availability in the unlicensed spectrum - especially at high frequencies - and to the development of Licensed-Assisted Access (LAA) technology in 3GPP Release 13 [2] .

The most attractive unlicensed band is the 5 GHz band, which is not as crowded as the 2.4 GHz ISM band and has a good portion of continuous spectrum globally available. However, it is important to consider that both Wi-Fi and radar systems already work in this band, and then LTE LAA must fairly coexist with these technologies. Several coexistence mechanisms have been proposed also depending on the regulatory requirements of a region. In Europe and Japan a technique such as Listen-Before-Talk (LBT) is needed, while in other markets like U.S and China it is not required as presented in [3].

The seek for new spectrum at high frequencies is a common element with the new generation 5G, that will use higher frequencies for commercial deployment (e.g. millimeter-wave frequencies in the range 24 GHz - 30 GHz). As such LTE-Licensed Assisted Access with its combination of licensed and unlicensed spectrum, working at high frequency band and based on a small cells architecture, is a significant milestone toward the 5th generation.

Working with contiguous portions of spectrum is also beneficial in solving the licensed bands issue of spectrum fragmentation, that is related to current limitations of number of downlink antenna ports managed by commercial devices. In fact, the aggregation of non contiguous licensed bands requires each band to have a dedicated antenna port number, thereby reducing the possibilities of MIMO for several carriers.

The purpose of this work is to observe the behaviour and the performance of LTE LAA in indoor environments, analyzing user throughput in downlink in compliance with fair coexistence with Wi-Fi. This paper is organized in five sections. In section II, the technology and the scenario of interest are presented; sections III and IV deal with simulation analysis and achieved results. Then in Section V, conclusions are drawn.

II. Technology and Scenario

Spectrum aggregation in LTE LAA requires at least one carrier anchored in licensed band and then carriers on unlicensed band. The primary cell (PCell) provides a user equipment

(UE) with the LTE services and reliability, the secondary cells (SCells) in the unlicensed supply with more bandwidth to get a performance boost in throughput as a supplemental downlink (SDL). The actual availability of the unlicensed spectrum depends on the fair coexistence mechanism used. In the standardization process of LAA, 3GPP has chosen LBT as a technique to present a technology that meets global regulations.

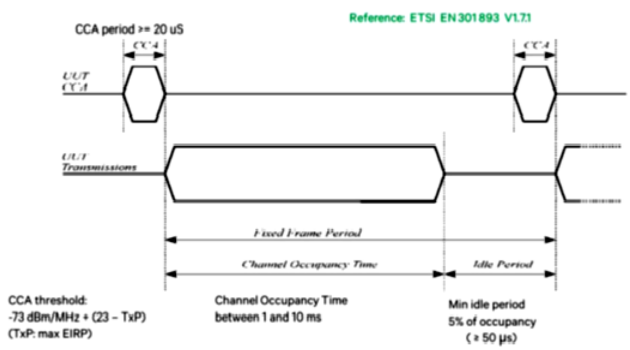

Fig. 1. Listen Before Talk mechanism

In this coexistence procedure, based on energy detection (ED) of Wi-Fi and other potential sources, the LAA node checks, before data transmission, the availability of the medium through a clear channel assessment (CCA), ensuring fair sharing in the unlicensed 5 GHz band. Among the four different deployment scenario in [2], this investigation has focused on the one characterized by carrier aggregation between licensed and unlicensed small cells without macro cell coverage. The scenario of interest for the evaluation of LTE LAA thereby is an indoor environment, as an office in a single-floor building, 120 m x 50 m, where two different operators Wi-Fi and LTE LAA deploy small cells. Each operator has several users in fixed positions, with no presence of mobility. This aspect of mobility will be addressed and explained more specifically in the section related to the simulator adopted. The scenario of deployment is described as it follows:

- Operator A: LTE – LAA with 3 eNBs, 20 UEs;
- Operator B: Wi-Fi: 2 base stations (BS) and 16 clients (STAs).

Both Wi-Fi access points (APs) and LTE LAA eNodeBs (eNBs) share 20 MHz of spectrum at 5.18 GHz; LTE licensed bands are 2100 MHz and 2600 MHz with a bandwidth of 15 MHz or 20 MHz, depending on the availability of the mobile operator. Our interest has been to compare downlink performances in terms of average user perceived throughput of this unlicensed deployment, with the performance offered by a completely licensed scenario in which LTE operates in band 1 (2100 MHz) and band 7 (2600 MHz), with an overall bandwidth up to 40 MHz.

Through the use of a network simulator - with a limitation on the modulation coding scheme up to 64QAM - these main cases have been evaluated:

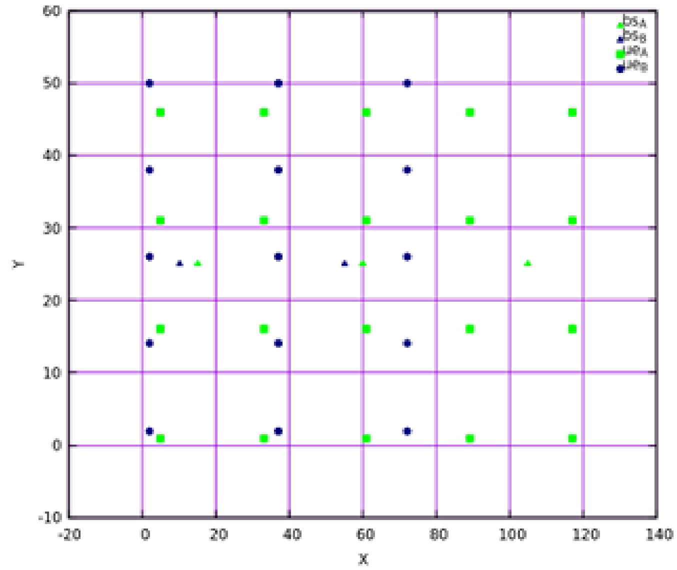

Fig. 2. Simulation scenario

1) 35 (or 40) MHz completely licensed LTE using MIMO 4x4 and MIMO 2x2, respectively on 20 MHz in Band 1 and 15 (or 20) MHz in band 7;
2) 35 (or 40) MHz LTE LAA using MIMO 4x4 and MIMO 2x2, respectively on 15 (or 20) MHz in Band 1 and 20 MHz in 5 GHz band;
3) Use of MIMO 4x4 for both licensed LTE and LTE LAA.

To complete the analysis of LAA performance and to understand the advantages offered by such a technology, that will be commercially deployed by the end of the 2017, also tests on a pre-commercial smartphone have been of key importance.

III. Analysis and Simulations

The analysis of LTE LAA behaviour and its contribution to the increase of system capacity is carried out by using ns-3, that is a discrete event (DE) network simulator [4]. This simulator has been chosen and funded by Wi-Fi Alliance to study the coexistence of LTE LAA with Wi-Fi, and it provides well implemented LBT mechanisms [5]. Such a collaboration indeed resulted in a Wi-Fi Alliance contribution to 3GPP RAN1 in November 2015 and in August 2016 [6].

In the described scenario, the traffic model implemented in ns-3 for both Wi-Fi and LTE LAA is the FTP Model 1 [2], based on a Poisson process for files arrival, with transmissions of files of size 512KB in packets of 1448B. The parameter λ, representing the arrival time of the Poisson distribution, is set to be equal to 1: in this way packets are sent each 1 over λ second, i.e. each second. This traffic model thereby characterizes the simulation of an entertainment service, based on the transmission of high quality videos.

To study the potential of LTE LAA as an effective SDL, it has been necessary to impose a fixed position of the UEs inside the scenario implemented on the ns-3 simulator, in order to ensure the effectiveness of the model. The absence of mobility and randomness make it possible to evaluate the same scenario both at licensed frequencies and unlicensed frequencies. Therefore, the downlink performance at 5 GHz band can be supplementary added to the licensed one, with no change of path-loss conditions using the propagation model ITU Indoor Hotspot (InH) [7].

An important parameter for simulation results is the energy detection threshold adopted in the LBT mechanism: it can assume values of -62 dBm, -72 dBm and -82 dBm representing the energy level above which LTE devices sense the medium as occupied. The behaviour observed in the simulation session that has been carried out, induced us to choose -72 dBm as standard value: it allows in fact both to respect Wi-Fi and not to affect excessively the performance of LAA, representing thereby an intermediate solution.

Some changes have been applied to the ns-3 code, in order to obtain the possibility of estimating more thoroughly LTE LAA potential. In fact, current structure of the simulator concerning multi antenna techniques only allows to simulate up to MIMO 2x2. From the tables 7.1.7.2.2-1 and 7.1.7.2.5-1 [36.213] it can be observed the Transport Block Size (TBS) ratio passing respectively from one-layer to two-layer and from two-layer to four-layer. It follows that on average in MIMO 2x2 the TBS is doubled and in MIMO 4x4 is quadrupled. Hence, by modifying the function $GetTbSizeFromMcs$ in "lte-amc.cc" it has been introduced such implementation. It has also been added a check on the MCS value through an if clause, to ensure the use of high antenna techniques only in cases of optimal channel conditions.

Thanks to this achievement it can be simulated also the case of LTE LAA using MIMO 4x4 both on licensed and unlicensed frequencies, going even further the configuration foreseen in the first commercial deployments, since it will allow just MIMO 2x2 on the 5GHz band.

The output of the simulation is the user perceived throughput (UPT) and the aim of this investigation is to observe if simulation results confirm the boost observed in theoretical studies, that could lead to peak data rate of around 1 Gbps.

Then it is worth, before the analysis of results obtained, to present a computation of the maximum throughput achievable by LTE LAA. When using the unlicensed spectrum, the computation is different from the licensed case due to the use of LBT mechanism that implies a CCA period equal to 20 μs as reported in [ETSI 301.893]. Because of the features of LTE PHY layer and the functionalities of the scheduler, this period has to be mapped within one subframe (1ms) or at least within half-subframe (0.5 ms). After the CCA period the LTE node can transmit in DL for 8 ms or 10 ms, according to the Channel Access Priority Class defined in Table 5.1.1-1 [8].

Thereby, choosing a common and conservative case with class p equal to 4, $Tmcot, p = 8ms$ and CCA period of 1 ms, the scheduling rate is $8/9$ – 8 subframes for transmission and 1 subframe for CCA – the throughput on the physical layer is:

Channel Access Priority Class (p)	m_p	$CW_{\min,p}$	$CW_{\max,p}$	$T_{m\cot,p}$	allowed CW_p sizes
1	1	3	7	2 ms	{3,7}
2	1	7	15	3 ms	{7,15}
3	3	15	63	8 or 10 ms	{15,31,63}
4	7	15	1023	8 or 10 ms	{15,31,63,127,255,511,1023}

Fig. 3. Channel Access Priority Class

$$391632 + 3 * \frac{8}{9} * 195792 = 913744 \frac{bits}{TTI} = 913.7 Mbps$$

Hence, the maximum theoretical throughput for LAA using 60 MHz in the unlicensed spectrum is about 914 Mbps. This results it is obtained in a configuration consisting of 20MHz and MIMO 4x4 in licensed band, plus 60MHz and MIMO 2x2 in unlicensed 5GHz band; all the carriers used 256QAM.

IV. Results

In this section, the results of simulations on LTE Licensed Assisted Access performances are presented and analysed. It is worth remembering that different deployment configurations are evaluated for the primary purpose of comparing the data-rate achieved using the unlicensed spectrum for supplemental downlink, with the data-rate offered by entirely licensed spectrum. The results of this study can help to understand the LAA potential for future commercial deployment in the path toward 5G and with the goal of an ever-better user experience. As already written, all the simulations carried out are based on the following settings.

Parameter	Wi-Fi	LAA	LTE
Transport	FTP Model 1		
λ	1		
File Size	0.5 MB		
Energy Detection Threshold		-72 dBm	

Fig. 4. Simulation settings

So, the first comparisons between licensed and unlicensed solutions refers to the case with 35 MHz and 40 MHz of overall bandwidth with a mixed use of MIMO 4x4 and MIMO 2x2.

The results of this test-case are useful to understand the possibilities of a deployment scenario that is currently adopted by several mobile operators: in fact, in many cases there are only 15 MHz available on the band 2600MHz. With 35 MHz of bandwidth, the completely licensed solution is capable to offer higher data rate than the unlicensed one; anyway the gap it is not too wide. In fact, LTE LAA provides an average UPT that is lower of about 17 Mbps. That difference can be interpreted also as part of the loss due to the CCA of LBT mechanism, for the respect of Wi-Fi. Clearly an entirely licensed LTE does not

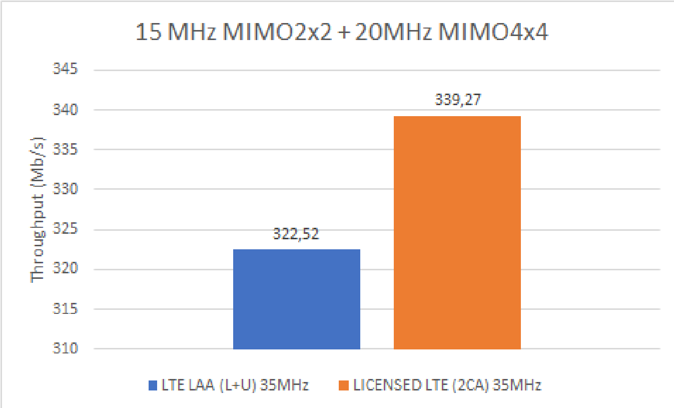

Fig. 5. Comparison LTE vs. LTE LAA in 35 MHz

suffer at all for the compresence of Wi-Fi system. Then the second test-case of interest is characterized by an increase of the available bandwidth, considering an availability of 40 MHz in total. To use larger licensed spectrum clearly it is not easy, since the high costs and limited nature of such resource. Again,

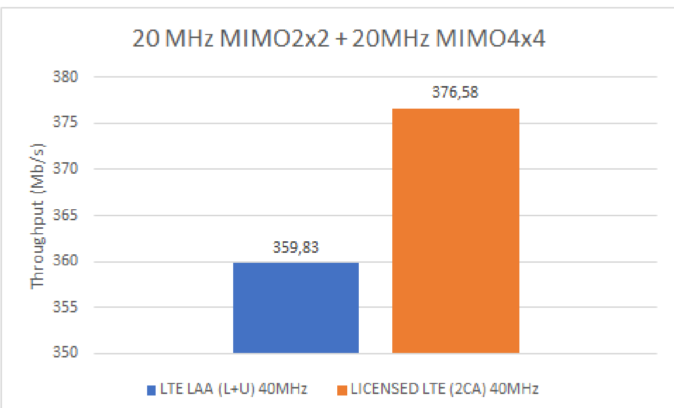

Fig. 6. Comparison LTE vs. LTE LAA in 40 MHz

the comparison reveals that the completely licensed case offers higher data-rate, with a difference similar to the previous one. LTE LAA prove to offer sufficiently high throughput levels to represent a valid alternative. Such an alternative could indeed provide mobile operators with the possibility to offload data in unlicensed band; furthermore the use of the unlicensed solution could avoid interference between macro and small cells. Third test-case is represented by the MIMO 4x4 configuration available for both licensed and unlicensed bands in parallel, considered for 40 MHz of bandwidth. Clearly it shows an increase of the UPT values for both licensed and unlicensed solution. As already said, this configuration represents a forecast and a simulation of a deployment scenario that will not be immediately realized commercially. It is also worth noting that the possibility to exploit MIMO 4x4 is strictly related to optimal channel conditions, and then to high MCS values. The analysis of the simulation results should be well contextualized, taking into account which are the

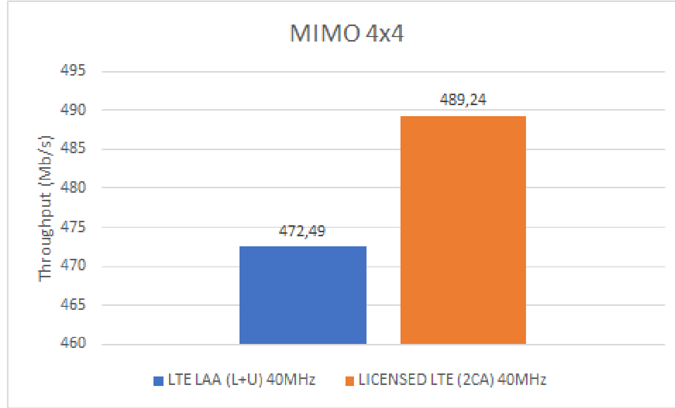

Fig. 7. Comparison LTE vs. LTE LAA in MIMO 4x4

spectrum possibilities for mobile operators. Licensed solution on the one hand offers better performances in the direct comparison with unlicensed solution if considering just 40 MHz of bandwidth. On the other hand it entails high costs and limited opportunities for trying to achieve data-rates over the limits of LTE-A. It is in fact extremely difficult to find more than 65 MHz of licensed spectrum available, whereas a large amount of unlicensed spectrum can be exploit working in the 5 GHz band.

So, the simulation results indicate and suggest that the aggregation of unlicensed spectrum concretely can represent the solution to overcome the limits that mobile operator are nowadays facing. This fact can be effectively observed through the results obtained by tests on the LTE LAA performance using a pre-commercial smartphone – based on downlink category 16 modem - with the capabilities to support operations in unlicensed spectrum and a pre-commercial network equipment.

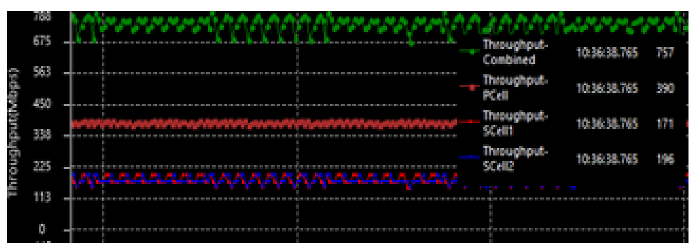

Fig. 8. LTE LAA throughput

Thanks to these tests it is possible to observe how a LAA device practically works and performs. In particular, for the results exposed further the configuration used consists of one PCC FDD 20 MHz, MIMO 4x4 (licensed) plus two SCCs LAA MIMO 2x2 20MHz per carrier. Even though it is not yet the maximal configuration, exploiting 40MHz and not 60 MHz from unlicensed spectrum, it is helpful to understand the potential of LTE LAA technology. The figure reports the performances obtained when using LBT only for one SCC. In fact, the throughput of the SCell1 is equal to 171 Mbps due to the CCA presence of LBT for the 87.5% of the time; the

SCell2 instead performs a higher throughput as expected from the theory. Such a test demonstrates that LTE LAA can enable very high data rate, with the allocation of just 20 MHz of licensed spectrum. Hence, to aggregate progressively more and more bandwidth from the unlicensed spectrum can effectively be the solution to achieve throughput in downlink around the Gigabit.

V. Conclusions

LTE Licensed-Assisted Access features and its potential to overcome the data rate issue, coexisting fairly with pre-existing technologies has been discussed in this paper. The possibility to reach the Gigabit LTE offered by LAA are such that its commercial deployment is expected to be the second half of 2017. Being on the path of hyper-dense networks and providing end-users with excellent reliability and enhanced experience, LAA is at this moment crucial and strategical towards 5G [9].

Hence simulations for indoor scenarios have helped to understand the improvements brought by the unlicensed spectrum to the network capacity, and the behaviour in presence of Wi-Fi using a LBT channel access manager, for a friendly coexistence.

The results of this analysis promote and encourage the use of LTE LAA, especially considering that it will allow in the upcoming commercial deployments to use up to 60 MHz contiguous, from the unlicensed spectrum, as supplemental downlink. It means that on the one hand the use of continuous unlicensed spectrum offers higher data rate, on the other hand it gives a chance to reduce the number of device antenna ports, so opening for optimization of MIMO deployment on several carriers.

Moreover, to operate with unlicensed frequencies provides operator with the possibility to offload data from licensed bands. Thereby, it implies an optimization of the scarce licensed resources. It entails also a reduction of the interference at licensed frequencies currently existing among macrocells outside and small-cells inside the buildings: an indoor deployment as the one described in the simulation scenario will allow to avoid conflicts, since it will need just 20 MHz of licensed spectrum to get high throughput in downlink.

The focus of this research has been the downlink (DL) aspects of LAA already defined in LTE Release 13. Experimental results of this study are restricted to the cases of one or two secondary component carriers in unlicensed spectrum studies because of current limitation of ns-3 software and capabilities of first commercial compatible with LAA. Future works will explore the performance of LAA technology using more carriers, higher modulation order and number of antennas, through testbeds and improved simulation tools. Furthermore the evaluation of uplink (UL) LAA - recently defined in Release 14 that has just been frozen in September 2017 - is left to future researches.

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